Proceedings of the 2021 AIAA/IEEE 40th Digital Avionics Systems Conference (DASC), 3-7 October, San Antonio, USA
DOI:10.1109/DASC52595.2021.9594407

Detect and Avoid Considerations for Safe sUAS Operations in Urban Environments

Victor Celdran Martinez
School of Aerospace, Transport and Manufacturing
Cranfield University
Cranfield, United Kingdom
V.Celdran-Martinez@cranfield.ac.uk

Bilkan Ince
School of Aerospace, Transport and Manufacturing
Cranfield University
Cranfield, United Kingdom
b.g.ince@cranfield.ac.uk

Praveen Kumar Selvam
Department of SciTec
University of Applied Sciences Jena
Jena, Germany
PraveenKumar.Selvam@ieee.org

Ivan Petrunin
School of Aerospace, Transport and Manufacturing
Cranfield University
Cranfield, United Kingdom
I.Petrunin@cranfield.ac.uk

Minguk Seo
School of Aerospace, Transport and Manufacturing
Cranfield University
Cranfield, United Kingdom
Minguk.Seo@cranfield.ac.uk

Edward Anastassacos
Director
HEROTECH8
Cranfield, United Kingdom
Edward.Anastassacos@herotech8.com

Paul G. Royall
Institute of Pharmaceutical Science
Department of Pharmacy
King's College
London, United Kingdom
Paul.Royall@kcl.ac.uk

Adrian Cole
School of Aerospace, Transport and Manufacturing
Cranfield University
Cranfield, United Kingdom
A.C.Cole@cranfield.ac.uk

Antonios Tsourdos
School of Aerospace, Transport and Manufacturing
Cranfield University
Cranfield, United Kingdom
A.Tsourdos@cranfield.ac.uk

Sebastian Knorr
Department of Electrical and Computer Engineering
University of Applied Sciences Jena
Jena, Germany
Sebastian.Knorr@eah-jena.de

***Abstract*—Operations involving small Unmanned Aerial Systems (sUAS) in urban environments are occurring ever more frequently as recognized applications gain acceptance, and new use cases emerge, such as urban air mobility, medical deliveries, and support of emergency services. Higher demands in these operations and the requirement to access urban airspace present new challenges in sUAS operational safety. The presence of Detect and Avoid (DAA) capability of sUAS is one of the major requirements to its safe operation in urban environments according to the current legislation, such as the CAP 722 in the United Kingdom (UK). The platform or its operator proves a full awareness of all potential obstacles within the mission, maintains a safe distance from other airspace users, and, ultimately, performs Collision Avoidance (CA) maneuvers to avoid imminent impacts. Different missions for the defined scenarios are designed and performed within the simulation model in Software Tool Kit (STK) software environment, covering a wide range of practical cases. The acquired data supports assessment of feasibility and requirements to real-time processing. Analysis of the findings and simulation results leads to a holistic approach to implementation of sUAS operations in urban environments, focusing on extracting critical DAA capability for safe mission completion. The proposed approach forms a valuable asset for safe operations validation, enabling better evaluation of risk mitigation for sUAS urban operations and safety-focused design of the sensor payload and algorithms.**

Keywords—Detect and Avoid (DAA), small Unmanned Aircraft Systems (sUAS), Safety Operations, Risk Mitigation in Urban Environments.

This work is supported by Innovate UK funding, grant number 84765

I. Introduction

For years, a global market for Unmanned Aerial Systems (UAS) has been developing. The global UAS market is estimated to be USD 27.4 billion in 2021 and is projected to reach USD 58.4 billion by 2026, at a Compound Annual Growth Rate (CAGR) of 16.4% from 2021 to 2026 [1]. Small Unmanned Aircraft Systems (sUAS) are rapidly used in urban environments to accomplish various operations such as medical deliveries, commercial package delivery, critical infrastructure inspection, precision agriculture, and search and rescue operations. These operations require establishing safety mechanisms at both the infrastructure and sUAS application levels. The use of sUAS in urban environments meets the definition of a safety-critical system whose failure could lead to loss of life, considerable damage to property, or environmental damage. The problem is multifaceted, and appropriate levels of safety can only be obtained at the systems level by holistically considering the hardware, software, and operator aspects of the infrastructure and their interactions with potentially untrusted sUAS [2]. Safety risks and required mitigations are of particular interest for an urban infrastructure that manages sUAS in the monitored airspace. This includes awareness of their state, location, and characteristics while ensuring that new sUAS entering the airspace meet minimum safety-related performance requirements.

This work focuses on evaluating safety for sUAS operations within urban environments and discussing practical considerations for the development of DAA capabilities for safe operations. The ability to Detect and Avoid is a critical enabler for the safe integration of sUAS into the airspace. One of the primary challenges of such capability is meeting Civil Aviation Authority (CAA) CAP 722 requirements for detecting and avoiding other aircraft, when operating in an urban environment [3]. However, Beyond Visual Line of Sight (BVLOS) sUAS operations in a non-segregated airspace will not normally be permitted without an acceptable DAA capability [4]. DAA systems are intended to allow sUAS to "Remain Well Clear " (RWC) and avoid collisions with other airborne traffic. In order to do so, an objective definition of RWC is required. DAA is required to provide detection and guidance to maintain RWC and, if it is lost, recovery guidance is required in order to regain it. The DAA system should provide the following functions to support DAA capability [5]:

- *Detection* - Use one or more onboard sensors to detect obstacles.
- *Track* - Use detection results to estimate obstacles positions and velocities.
- *Evaluate* - Assess collision risk of tracked obstacles.
- *Prioritize* - Assess threat priorities/hazards (urgency levels).
- *Declare* - Alert remote pilot to avoidance action required.
- *Determine* - Decide what action to take.
- *Command* - Communicate the action for execution.
- *Execute* - Execute the commanded action.

The main contributions in this paper for safer DAA urban operations are as follows:

- A review of the state-of-the-art technologies used for DAA.
- A set of representative urban scenarios, incorporating elements of DAA potential challenges, such as irregular buildings height, vegetation, and crowded airspace.
- Heterogeneous missions for the defined scenarios, covering a wide range of practical cases.
- Complete scenarios simulation by integrating the platform model with DAA supporting technologies, including navigation, communication and collision avoidance.

The remainder of the paper is structured as follows: Section II presents the Detect and avoid technologies. Section III sets out the DAA approach in simulation and the process of Well Clear volumes in sUAS. Section IV compares and analyzes the performance and practical considerations of DAA. Section V concludes the proposed DAA approach.

II. Detect and Avoid Technologies and Architectures

The literature review of the DAA includes technologies and approaches that could be used on an sUAS and enable the

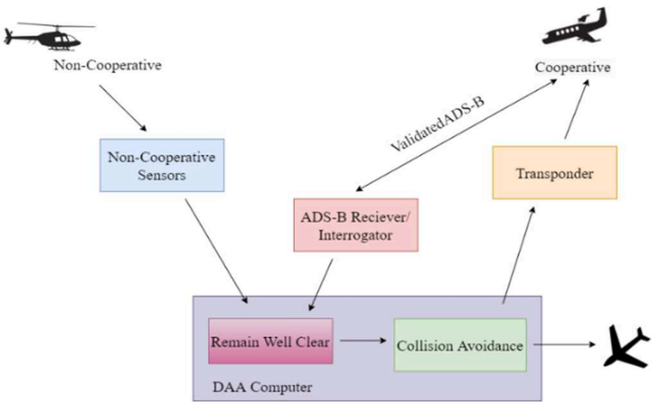


Fig. 1 Overview of DAA technologies

CAA to understand the types of DAA available for sUAS operating in the airspace. Initially, the DAA requirements are derived from sections 111 and 113 of Part 91 of the Federal Aviation Regulations (FAR). The FARs are part of Title 14 of the Code of Federal Regulations (14 CFR). FAR 91.111 addresses "Operating near other aircraft," while FAR 91.113 addresses "Right-of-way rules." FAR 91.111 prohibits operations, so close to another aircraft as to create a collision hazard. According to FAR 91.113, each person operating an aircraft must maintain vigilance to see and avoid other aircraft [6]. Many different existing systems propose DAA capabilities for UAS, such as Air Force's Multiple Sensor Integrated Conflict Avoidance (MuSICA)/Jointly Optimal Conflict Avoidance (JOCA) [7], the National Aeronautics and Space Administration's (NASA's) Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS) [8], the Terrestrial Acoustic Sensor Array (TASA), SARA's acoustic sense and avoid systems [9], Advanced U-space services and technologies (U3 and U4), SESAR U-space development of miniaturized, automated Detect and Avoid functionalities [10][11], a NASA's SAA algorithm of Independent Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS) [12], and the New Mexico State University and University of North Dakota Alliance for System Safety of UAS through Research Excellence (ASSURE). However, these DAA technologies for UAS are mainly focusing for larger aircrafts, whereas integrating DAA capabilities in sUAS is quite challenging. To define and understand the DAA problem, a standard system engineering approach was used to systematically approach the problem, including evaluating DAA requirements and potential technology solutions. Cooperative and non-cooperative technologies examined by performing a DAA function on the sUAS are shown in Fig. 1. Active and passive sensor systems are included in the discussion of non-cooperative technologies.

A. Well Clear Recommendation

The "Well Clear" recommendation of a DAA system combines a RWC function and an optional Collision Avoidance (CA) function [13]. The main differences between RWC and CA are shown in Table 1. The RWC function provides tactical maneuvers to remain Well Clear, while the CA function provides urgent maneuvers intended to prevent midair collisions [14]. The need for determining a Well Clear definition for UAS was identified early in Sense and Avoid

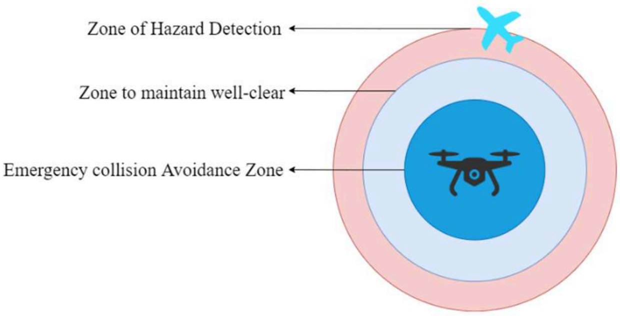


Fig. 2 Proximity of hazards

(SAA) system development. As the remote pilot of a UAS cannot provide the same 'see and avoid' mitigation for potential hazards, the UAS itself must be capable of performing an equivalent function. The proximity of hazards at different zones is illustrated in Fig. 2. One of the highest priorities for a "Well Clear" is the guarantee of staying within a given geospatial containment volume [15], where the separation is based upon the thread and the intruder aircraft. The RWC threshold and RWC volume, collision volume, and collision avoidance threshold are shown in Fig. 3 as defined in the International Civil Aviation Organization (ICAO) Remotely Piloted Aircraft System (RPAS) ICAO RPAS Manual [16].

Table 1: Main differences between RWC and CA [18]

	RWC	**CA**
Decision factors	Safety, acceptability, strategic	Safety
Responsibility	Depends on airspace (can be shared with pilot)	Pilot
Contact Air traffic control	Yes, notably if under clearance	If time allows
Start/End	Conflict/ Collision hazard or Clear of Conflict (CoC)	Collision hazard/NMAC or CoC
Time horizon	Few minutes	Tens of seconds
Maneuver	Smooth	Strong
Maneuver Constraints	Right of Way rules, clearance	None

There are different "Well Clear" concepts for UAS, such as a closest point of approach (CPA) and time-to-CPA from NASA; a time-based image with distance modifications from Massachusetts Institute of Technology Lincoln Laboratory, and an ellipsoidal idea defined by aircraft speed with varying vertical dimension from Air Force Research Laboratory [17]. In their work the Well Clear principles are tuned to a standard level of unmitigated collision using Monte Carlo analysis, resulting in tuned UAS Well Clear recommendations with an equivalent risk of a Near Mid-Air Collision (NMAC). Furthermore, the operational suitability of the Well Clear volume is evaluated using Monto Carlo simulation, Human-in-the-loop simulation, Stressing Case analysis, and fast-time simulation.

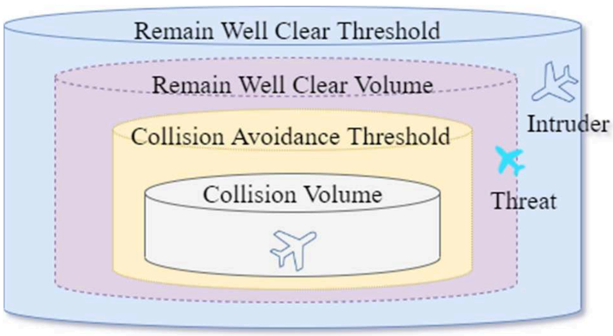


Fig. 3 Definition of Well Clear and Collision Avoidance Volume

The Traffic Collision Avoidance System II Resolution Advisory Rate (TCAS II RA), controller acceptability considerations, Well Clear volume, cross-track deviation, vertical deviation, maneuver initial point, CPA miss distance/time given Well Clear violation and mitigated risk ratio are the metrics evaluated during the different simulation process as mentioned above. For the sUAS these functions required redefinition. Rather than including separate RWC and CA functions, sUAS will include one level of alerting and guidance, with the separation volume based on intruder type [19]. The Well Clear recommendations inform the scalable separation volume, and the considered metrics were probability of a NMAC, probability of loss of Well Clear (PLoWC), horizontal miss distance, and vertical miss distance.

Also, there have been studies on collision risk assessment [20] [21] based on the dynamic model of the sUAS, but these methods are mathematically complex to be utilized online.

B. Cooperative Technologies

1) Airborne Collision Avoidance System (ACAS): The Detect and Avoid function includes two functions to UASs: Traffic Avoidance (TA) and Collision Avoidance (CA). TA allows you to keep a safe distance from other airspace users. CA enables last-second maneuvering to avoid NMAC. Air traffic control ensures aircraft separation, so TA is not required in controlled airspace. Pilots currently perform collision avoidance with the assistance of dedicated avionics, such as TCAS II. Existing collision avoidance logic, on the other hand, is reaching its limits. Air Traffic Management modernization efforts (NextGen and SESAR) have addressed this issue by developing new collision avoidance technologies, updating ACAS II [22]. The group of experts tasked with developing this new collision avoidance technology settled on a decision-theoretic planning method called ACAS X. This method is available in several variations based on a common framework. ACAS Xa is designed for large aircraft, ACAS Xo is for special operations, ACAS Xu is for unmanned aircraft, ACAS Xp is for general aviation and ACAS sXu is for sUAS. As with other ACAS X variants, sXu consists of two primary modules, the Surveillance and Tracking Module (STM) and the Threat Resolution Module (TRM).

The function of the ACAS sXu STM is to present an estimated state of the location to the Threat Resolution Module TRM. The ACAS sXu addresses the critical challenges of providing timely DAA advisories that are robust to noisy surveillance sources and the uncertain nature of aircraft future trajectories. These difficulties are overcome by modeling the DAA problem as a Markov Decision Process (MDP) [19]. The TRM typically consists of two action phases horizontal action phase and the vertical action phase. The vertical action phase consists of five actions: Clear-of-conflict (CoC), Do Not Climb, Do Not Descend, Climb, and Descent. The horizontal action phase consists of CoC, turn right and turn left actions. The ACAS sXu implementation includes two scaling options: one for sUAS vs sUAS and another for sUAS vs manned.

2) Automatic Dependent Surveillance-Broadcast: Automatic Dependent Surveillance-Broadcast (ADS-B) technology was introduced more than two decades ago to improve surveillance within the airspace. ADS-B enables autopilots and ground-based stations to detect other similarly equipped aircraft in the airspace with higher efficiency precision [23]. It automatically acquires parameters from relevant airborne equipment, Global Navigation Satellite System (GNSS), broadcasts to ground equipment and other aircraft information, such as aircraft position, altitude, speed, flight direction, atnd aircraft identification. It achieves true flight information sharing and has significant benefits in reinforcing ground-to-air, air-to-air, and ground-to-ground coordination. The aircraft is transmitting a signal containing aircraft broadcast information (ADS-B OUT), and the signal receiver receives the information if the aircraft meets the necessary specifications [24].

3) ADS-B Traffic Advisory System (ATAS): ATAS detects and alerts pilots to potential traffic conflicts using ADS-B. By combining ADS-B tracking data with proximity-prediction algorithms, ATAS monitors potential traffic conflicts [25]. When ATAS detects a conflict, it emits an audible alert (traffic callout). Conflicting aircraft are also highlighted on cockpit displays when such displays are available in an airplane. After receiving an ATAS alert, the pilot takes action following the operational rules in effect at the time. Unlike TCAS II systems, ATAS does not provide resolution advisories [26]. ATAS was designed to operate in the Visual Flight Rule (VFR) traffic pattern at small general aviation airports, where most general aviation collisions occur without excessive nuisance alerts.

C. Non-Cooperative Technologies

Non-cooperative technologies, which do not rely on other aircraft, are among the promising technologies for use in sUAS DAA systems. The non-cooperative technology differs from cooperative technologies in that they do not require the use of other aircraft in the same airspace to avoid collisions. The non-cooperative technologies benefit from the fact that they can detect both ground-based and airborne obstacles. These non-cooperative technologies are classified into two types: active and passive. To detect obstacles in the flight path, active systems are used by sending out a signal. Radar and laser techniques are examples of active systems. Passive systems do not send out a signal, instead of detecting signals emitted by the obstacles themselves. Examples of passive systems include electro-optical (EO), infra-red (IR), thermal, motion detection, visionary and acoustic systems.

1) Active Systems: The radar is one of the primary sources to detect the non-cooperative targets in the airspace. The radar can be equipped either onboard or ground-based for sUAS. The onboard Sense and Avoid (SAA) capability, known as Independent Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS), developed by NASA to support sUAS operations, provides autonomous guidance using the traffic radar tracks onboard radar. NASA and the Mid-Atlantic Aviation Partnership conducted the flight test to investigate the applicability and performance of a prototype commercially available sUAS radar to detect and track non-cooperative airborne traffic. The radar selected for this research was a Frequency Modulated Continuous Wave (FMCW) radar with 120-degree azimuth and 80-degree elevation field of view operating at 24.55GHz center frequency with a 200 MHz bandwidth [27]. The ground-based radar can be integrated with a Ground-Based DAA system (GBDAA). The GBDAA uses ground-based surveillance, tracking, and other capabilities to Detect and Avoid obstacles to sUAS [28]. SRC Inc. GBDAA radar system is one such example of a ground-based radar [29]. It is an integrated, flexible, and scalable approach that enables sUAS flights to Detect and Avoid another aircraft. This solution is based on the a Lightweight Surveillance and Target Acquisition Radar (LSTAR) system, with a low lifecycle cost. The radars in the LSTAR system are remotely operated and send their detection and tracking information to a central fusion processor. This information is then correlated with available data to provide a complete and robust surveillance network capable of meeting the DAA requirements.

Light Detection and Ranging (LiDAR) is becoming a promising technology for obstacle warning and avoidance in a variety of manned and unmanned aircraft applications. LiDAR's outstanding angular resolution and accuracy characteristics are coupled to its good detection performance in a wide range of incidence angles and weather conditions, providing an ideal obstacle avoidance solution, which is especially attractive in sUAS [30]. The Laser Obstacle Avoidance Marconi (LOAM) system is one such system, which was jointly developed and tested by SELEX-ES and the Italian Air Force Research and Flight Test Centre. The laser-based obstacle detection, warning, and avoidance capabilities are critical for ensuring the safety of flight operations [31]. Another example of the laser system for sUAS is the LiDAR Obstacle Warning and Avoidance System (LOWAS) [32]. It is a low-weight/low-volume navigation aid system specifically designed to detect potentially dangerous ground and aerial obstacles placed in or near the planned flight trajectory, providing timely warnings for the crew to implement effective avoidance maneuvers.

2) Passive Systems: The EO systems require light as a primary source to detect obstacles and have advantages compared to radar. The radar in the airspace has a disadvantage of its increased size and weight, large power consumption, and high price. But nowadays, low size, weight, and power (SWaP) sensors like EO are researched and used to detect aircraft the airspace[33]. The DAA system requirements apply to a broader range of operations and vehicles, including non-cooperative sUAS with low SWaP. This lower performance class of sensors aids sUAS operating at slower speeds and lower altitudes, where ADS-B transponders are not currently required., i.e., below 10,000 ft mean sea level (MSL) and 100 knots true airspeed (KTAS) [34]. EO sensor-based aircraft detection is developed quickly with deep-learning-based detection and recognition [35]. The main issue with EO/low SWaP sensor-based aircraft is their short detection range and weather dependencies.

The IR system, which aids the EO sensor detection at night, is not affected by electromagnetic interference and can measure distance to obstacle by using IR light radiated from objects. Thermal imaging sensors detect heat in all-weather operation, whereas motion detectors function by sensing the direction and velocity of objects [36]. The spatial-temporal filter detection methods have emerged as potential vision-based aircraft detection systems for the DAA problem (at least for detecting aircraft collisions from the airspace region). The detection system needs to be physically mounted on the platform to allow sensing in the direction of potential collision course aircraft.

SARA (Scientific Applications and Research Associates, Inc.) created a small acoustic sensor system for sUAS. The Terrestrial Acoustic Sensor Array (TASA) is an acoustic phased array system that detects aircraft, classifies collision threats, and commands evasive maneuvers to allow sUAS to fly BVLOS safely. TASA can detect aircraft even when their line of sight is obstructed by trees, buildings, or terrain features [9]. Another acoustic-based technology from SARA is the Passive Acoustic Non-cooperative Collision Alert System (PANCAS). It is used to detects and tracks the sound of aircraft engines, propellers, or aircraft rotors. The PANCAS sensor array comprises several microphones arranged so that they provide bearing information for sound at each frequency [37]. The microphone array determines the bearing angle in azimuth and elevation by utilizing phase differences at the microphones. Different types of non-cooperative technologies related to detection and range are compared and shown in Table 2.

Table 2: Different types of non-cooperative technologies [38]

Name	System	Detection range (km)	Detection information	Comparison
Synthetic Aperture Radar (SAR)	Active	35	Distance, relative bearing	Low accuracy
LiDAR	Active	3	Distance	Small view
Electro-Optical system	Passive	20	Relative bearing, elevation	Susceptible to weather, lacking in guidance range
Infrared (IR system)	Passive	4.4	Relative bearing, elevation	Not applicable to IMC
Acoustic system	Passive	10	Relative bearing, elevation	Time delay
Visionary System	Passive	1.9	Position, speed	Small range, affected by the performance of camera

III. DAA Simulation

Simulating aerial operations across urban areas is challenging due to the complex geometrical nature of the built-up environment that greatly impacts signal propagation and communication loss models. This section presents different software setups conceived to complement each other and covers a wider range of considerations regarding DAA assessment.

A. Mission environment

The core DAA simulation environment is developed in Systems Tool Kit (STK) software, a platform for mission and systems modelling [39]. In Fig. 4 an overview of the proposed simulation setup is presented, including complete platform design, urban scenery, authority requirements and realistic communication propagation model.

DAA capabilities are assessed for representative urban scenes and sUAS routes, alongside with communications and navigational coverage throughout each defined mission, ensuring the sUAS functionality to safely perform flight operations. The scene geometry is based on 3D tiles extracted from globe view data in Google Maps 3D at the city of Milton Keynes (United Kingdom), where a medical delivery mission is performed. Once the 3D data are captured [40], an assembly and scaling process is performed in Blender [41], followed by tiling and georeferencing though the Cesium Ion [42] pipeline, and then is finally imported into STK.

In Fig. 5, an overview of the flight phases is presented, featuring an actual representation of buildings, vegetation and streets at the mission location. The resulting scenery enables a more detailed study, for instance accounting for line of vision obscuration due to trees and urban canyons [1]. Therefore, DAA and GNSS navigation can be effectively assessed, for which the number of visible satellites is continuously monitored.

For the mission, a set of objects commonly found in urban scenes (buildings, ground vehicles, vegetation and sUAS) are defined according to the objectives of the simulation at every flight stage: takeoff, cruise and landing. The first two stages consider airborne threats, while the landing accounts for both airborne and ground-based threats. During takeoff, a ground-

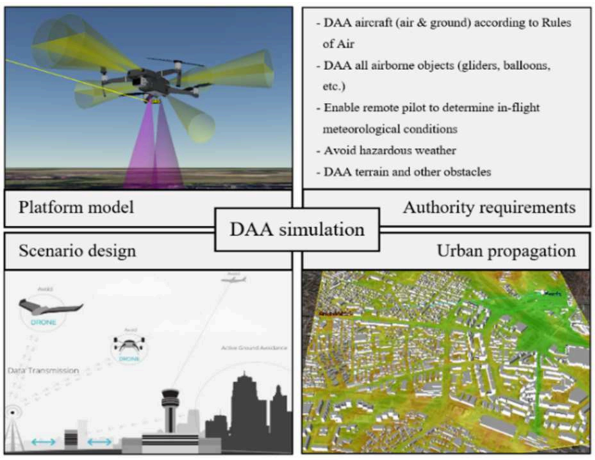
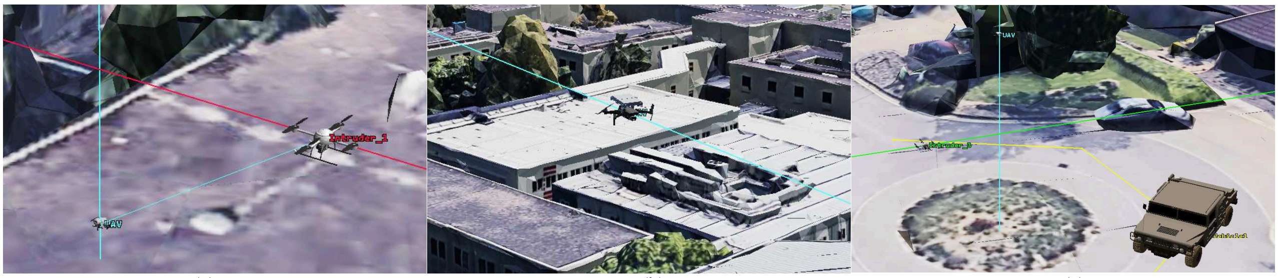


Fig. 4 DAA simulation components overview

[1] Urban canyons can be defined as places where the street is flanked on both sides by buildings and vegetation.



(a) (b) (c)

Fig. 5 Simulation environment urban scenes for each flight phase. Picture (a) shows a take-off stage, where a sUAS intruder flights nearby; in (b) a cruise over buildings and vegetation is presented, featuring a closer look to the platform and its payload; and finally, picture (c) showcases a crowded landing operation, where both ground and airborne objects are included invading the platform's Well Clear space

based obstacles Well Clear condition is assumed since the operator requires to prove these threats have been considered and properly mitigated; while on the other hand, unexpected conditions might lead to more crowded scenes for the landing stage, as for instance an emergency landing procedure, where the operator has no control over the potential obstacles and threats. Regarding the cruise, the flight takes place at a Well Clear height above the ceiling of the building, an extended practice for sUAS operations.

Airborne objects include the sUAS platform performing the mission and other airspace users/intruders, against which the DAA capabilities are tested. Each sUAS is defined in terms of a performance model, including maneuvers capabilities as maximum speed and rate, and an aero-propulsion model defines the powerplant and rotors specifications. Regarding onboard sensors, rather than extensive modelling for the numerous commercial options currently available for each category previously defined in Section II, an alternative approach is considered. The relative position and heading for each sUAS-obstacle pair are monitored during all flight stages, being analyzed by a hazard assessment metric based on safety volumes intersections, which are detailed at the end of subsection D.

Ground-based objects are composed of ground vehicles and mission equipment. Ground vehicles represent a potential collision threat during the landing phase, in addition to static obstacles, such as trees and buildings. Communication antenna supports the safe operations at the ground.

B. *Hazard Assessment*

The DAA algorithm developed in Simulink/MATLAB uses a sensor configuration consisting of the monocular camera and LiDAR to assess the hazard. The hazard assessment starts with the definition of safety volumes for the sUAS and the hazards. The safety volumes of the moving objects, such us sUAS, birds, etc., are defined by considering the velocity of the objects. As buildings, the safety volume is defined with a set of points apart from the obstacle with the same distance if the object has a simple shape for the static and large obstacles. The complex shapes' safety volume (e.g. trees) are defined as the minimum size of cylinder covering the object with a certain margin from the objects (see Fig. 6).

After the calculation of the safety volumes, the common volume V_i is calculated if a hazard i, whose safety volume intersects with that of the sUAS, exists. The score of the priority to avoid a certain hazard is calculated as follows. If the common volume V_i is 0, the score for the hazard i is 0. If the common volume V_i is non-zero, the score for the hazard i is

$$S_h = D_i V_i \tag{1}$$

where D_i is the danger level of the hazard defined by the user.

For example, since it is more dangerous to conflict with the building than sUAS, D_i of the building will be defined larger than sUAS. In order to implement a hazard assessment to the DAA algorithm, relevant criteria need to be prepared. The hazard criteria is determined by assigning priority values by assessing the relationship between the hazard score established in Eq. 1. The priority levels are decided through categorising the score, decided from Eq.1. To normalise the volume intersection data scaling constant term, c , is introduced by assessing the data values of the score, S_h.

$$S_h c \propto P_{criteria} \tag{2}$$

where $P_{criteria}$ is the priority criteria. Combining both Equation (1) and (2), the relationship between safety volume and danger levels calculated for priority levels are represented in Table 3.

Table 3. Priority Level Assignment

Obstacle Danger Level/ Safety Volume	**Emergency Intrusion (5)**	**Collision Volume (4)**	**Collision Avoidance Threshold (3)**	**Remain-Well-Clear Volume (2)**	**Remain-Well-Clear Threshol d (1)**
Intruder	5	4	4	3	1
Ground Vehicle	5	3	3	2	1
Building(s)	5	3	3	1	1
Foliage (Tree)	4	2	2	1	1

Finally, to provide a more extensive analysis over DAA vision-based techniques, an alternative simulation environment integrated using MATLAB, Simulink and Unreal Engine is proposed supporting the main simulation environment. The sUAS Toolbox on Simulink connects the DAA model to the simulation environment in Unreal Engine, which is populated with the scene's 3D tiles used in STK. This second setup allows the testing and implementation of collision avoidance techniques based on camera sensors, plus scene mapping via LiDAR. The objects positioning and behavior are inherited from the STK extracted states, providing a high-fidelity replica of the whole mission.

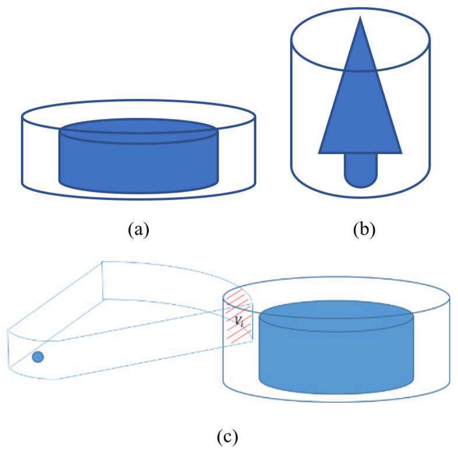


Fig. 6 Hazard assessment volumes representation: safety volume for static objects (a), safety volume for complex shapes (b), and intersection volume between sUAS safety volume (left) and static (c)object safety volume (right)

C. Simulation post-processing

Postprocessing of the mission data is performed in MATLAB [43], which is, once integrated into the STK environment, allowing the definition of scene parameters and extraction of object states from missions. From sUAS and intruder's flight attitude and georeferenced data, DAA capabilities are evaluated. For better accuracy of DAA simulation, STK-Unreal Engine connection is essential. Textures and mapping are translated to Unreal through exporting and importing as an object file where the textures are imported from their picture (.jpg or .png) equivalent to the Unreal blueprint scenario. A further connection is established using the Unreal-Simulink connection through sUAS Toolbox, as shown in Fig. 7.

The sensors implemented in Simulink for DAA testing are an onboard camera and LiDAR. Considering the onboard camera and LiDAR sensors on the sUAS, a sense and avoid algorithm is developed for hazard assessment implementing results and considerations from the previous simulation setups. To incorporate the risk assessment criteria, the intersected volume of the obstacle is processed and calculated using the disparity and segmentation map output of the Simulink 3D camera.

The segmentation map is used for obstacle identification and the disparity map is utilized to visualize the distance of obstacles using a threshold. LiDAR is used to validate the distances of objects to the depth image. The vision-based algorithm utilizes morphological operators and blob detection techniques on the disparity map, which is communicated through the Unreal Engine. A simple avoidance scheme is utilized to demonstrate the recognition of volume hazard intersections. The monocular camera and LiDAR implemented in the Simulink DAA algorithm allow the detection of obstacle centroids, areas, and their respective distances. A visual geometry is set within the vision-based algorithm to represent the safety volume as illustrated in Fig. 5c. Utilizing the position of the centroids and the relevant areas, the obstacle volume intersections can be calculated from the image. Priority levels are assigned using the criteria defined in Table 3, where the danger levels are defined through image segmentation.

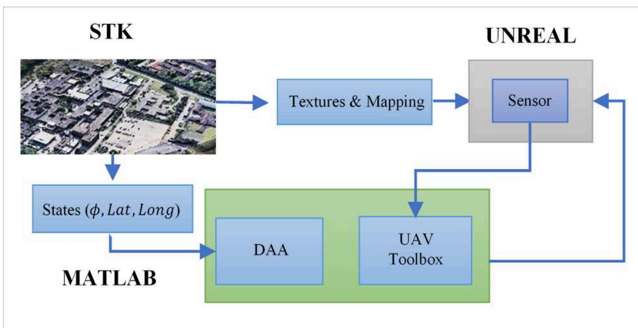


Fig. 7 STK – Simulink Integration

D. Communication effects

The RF communications analysis setup is modelled parallel to the one previously seen, although it uses Shapefile geometry (see Fig. 8), which is created from buildings blueprints extrusion. This RF model accounts for diffraction losses and buildings, terrain, and ground reflections, enabling strategic antenna placement and flight routes planning. Default STK's rain and clouds-fog models are applied to RF simulation, addressing atmospheric adversarial conditions during the mission.

IV. Analysis and Discussion

In this section, the results from the simulations address practical considerations to ensure safe operations. First, hazard assessment results are presented and discussed, analyzing how the different scene objects intervene in Well Clear volume keeping. Next, a set of practical considerations based on the developed simulation environment and the obtained results are presented.

A. Hazard assessment simulation results

The DAA utilized in Simulink is compared to the object detection in STK without avoidance. Detection in STK is achieved by defining a sensor with LiDAR characteristics, which calculates the distance, centroid positions, and the volume of obstacles defined in Table 3. Results are plotted in MATLAB to achieve accuracy using the same timesteps, t_s, for better understanding of the hazard assessment between the two synthetic environments. The takeoff and landing phase present more challenges than the cruise phase, as expected due to the greater number of obstacles found. In Fig. 9 and Fig. 10 the resulting prioritization and collision avoidance for these two phases can be found; the corresponding scenarios from STK are represented in Fig. 5.

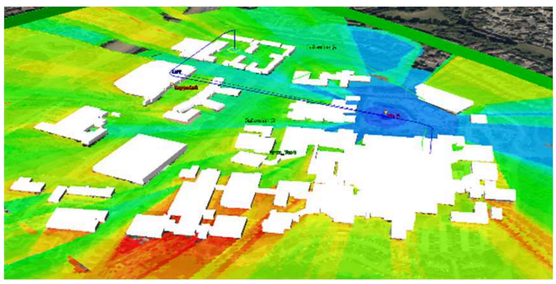
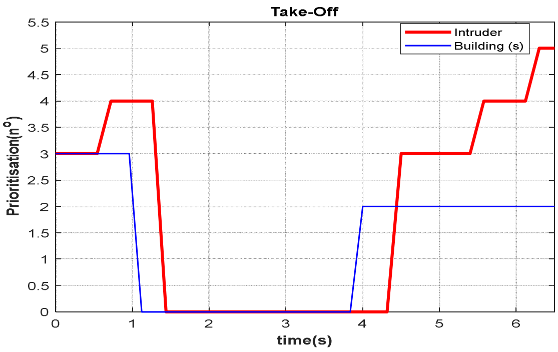
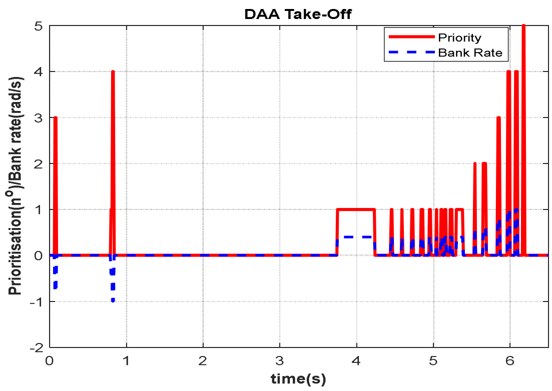


Fig. 8 Communications coverage simulation, based on Shapefile geometry, for a 1 m antenna height. While closer and in-line-of-sight zones prove a robust coverage (blue), areas behind buildings suffer from severe degradation (red)

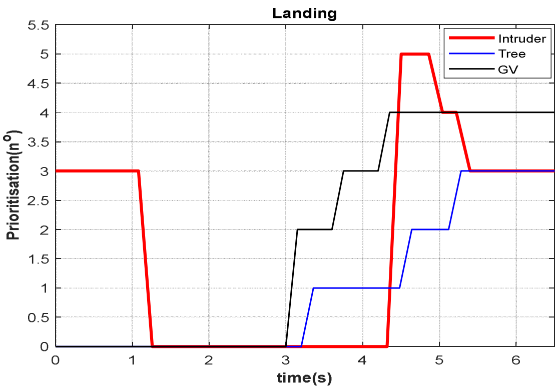


(a) Collision volume obstacle prioritization during takeoff

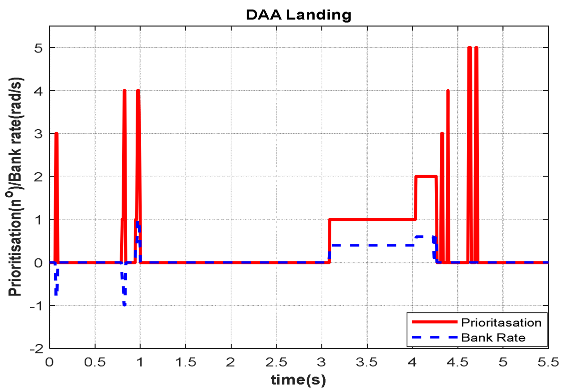


(b) Avoidance prioritization during takeoff

Fig. 9 Takeoff phase hazard assessment simulation results



(a) Collision volume obstacle prioritization during landing



(b) Avoidance prioritization during landing

Fig. 10 Landing phase hazard assessment simulation results

From the prioritization without avoidance in STK (Fig. 9a and Fig. 10a) one can note that the avoidance input for the intruder sUAS presents a higher rate of change than the building during the takeoff, given the change in distance to the platform. However, for the landing phase example, the ground vehicle plays a major role in the final stage until the intruder sUAS suddenly enters the airspace, acquiring a higher degree of priority. These roles could be reverted for a different situation; however, it is worth mentioning that moving objects risks generally monopolize the prioritization over static objects.

Once collision avoidance is introduced (Fig. 9b and Fig. 10b), the prior results are validated, conferring higher priorities a greater banking angle (negative and positive values indicate left and right turns, respectively), while lower priorities result in less aggressive maneuvers. The required bank angle is commanded to the control unit and executed to maintain a Well Clear distance from it.

B. Practical Considerations

From the obtained results in simulation, the following points are presented to be considered for practical applications of the Detect and Avoid systems:

1) sUAS navigation accuracy: The avoidance is conducted based on the information about the states of the sUAS and the obstacles. Thus, the performance of the avoidance algorithm is highly affected by the accuracy of the sUAS state information from the navigation system. Additionally, navigation accuracy can be severely degraded in built up environments, including multi-path problems. Therefore, navigational equipment redundancy is strongly advised. Urban and vegetation canyons are advised to be avoided during all flight phases if possible, or adequately mitigated otherwise. For instance, in Fig. 11 Global Positioning System (GPS) loss is presented, transitioning from complete to zero coverage in a short distance due to trees obscuration. These issues can be addressed by implementing redundancy in the system, such as multi-constellation/frequency GNSS systems. Finally, while theoretically a minimum of satellites would suffice for GNSS navigation, in practice accessing under 10 satellites might be considered poor coverage for a sUAS and prevent it from

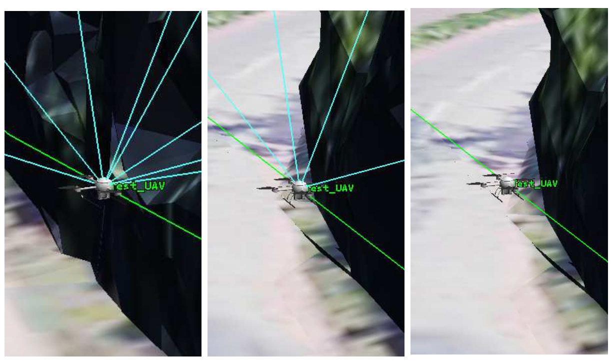


Fig. 11 GPS number of satellites visibility when entering an urban canyon. From left to right, from an initial number of 8 satellites, after a few meters the count descents to 4, and finally to 0, endangering the mission success

taking off, postulating GNSS signal loss is a major concern for urban operations.

2) *Noise or bias on sensors to detect obstacles:* Noise or bias on sensors will directly affect the performance of the detection algorithm. This will also affect the performance of the avoidance algorithm, since the avoidance is conduced based on the target information, which is estimated by the detection algorithm of the sUAS.

3) *Computational delay:* If a fast obstacle suddenly appears, the sUAS must react rapidly for safe operation. Thus, the computational delays affect the performance of the Detect and Avoid algorithm, especially in urgent cases.

4) *Weather:* It has a direct effect on the performance of the sUAS in various ways. Wind makes it difficult to control the attitude of the sUAS to follow the path. Rain can increase the noise on the camera image, which can degrade the performance of the detection algorithm. Rainfall can also reduce the RF coverage due to signal absorption by water droplets, a phenomenon observed in simulation results by significantly reducing the effective range of communications. In practice, this can often be experienced after heavy rainfall.

5) *Communications:* An interrupted datalink for cooperative DAA compliance is required to remain secure throughout the whole mission, constantly receiving airspace information and broadcasting the sUAS flight data. Additionally, for remotely piloted flights where the DAA capabilities provide the operator with airspace information and maneuver advice against non-cooperative traffic, it is essential to continuously send commands to the sUAS and receive the flight data at the ground station. According to simulation results, inner patios and building's proximity tend to be with zero to low coverage areas and abrupt terrain elevations. Therefore, ground-based equipment should be strategically located at a Well Clear spot, ideally at a certain height, as for instance an in-route building rooftop. This alternative antenna placement result is illustrated in Fig. 12, placing the transmitter on a building roof with undisturbed visibility over the flight path, providing datalink robustness along the mission duration.

V. Conclusion

This paper presents a comprehensive review of the state-of-the-art DAA technologies in conjunction with simulation of realistic urban scenarios for DAA potential challenges assessment. Different missions are designed and executed for representative scenes accounting for the common threads for each of the flight phases. Relevant factors such as RF degradation and navigational challenges, including urban canyons, complete the proposed simulation environment, complemented with DAA hazard assessment leading to effective threat identification.

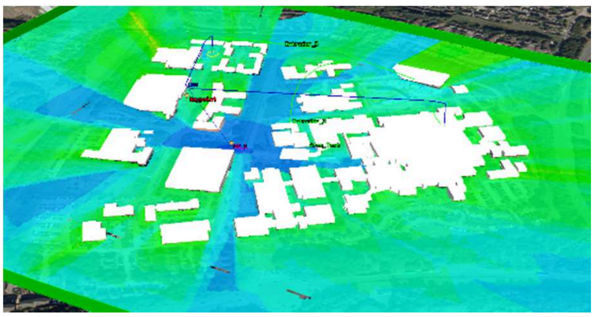


Fig. 12 Alternative antenna placement RF regional analysis for Fig. 8 scene

Compared to normal takeoff and landing over DAA takeoff and landing, the conflict of hazard mitigation and collision avoidance rate is higher. The obtained results show that DAA considerations integrated into sUAS have more significant collision avoidance and higher safety while operating in the airspace.

In the future, this work can be extended with path planning and navigation algorithms and Simultaneous Localization and Mapping (SLAM) to support the sUAS, equipped with DAA technologies, locating itself in the urban environment. The capabilities of the volume intersection could be improved by accounting in the direction of the dynamic obstacles, possibly by utilizing the Doppler effect and the angle to the obstacle. Regarding communications aspects for urban environments, the analysis can be expanded by implementing cellular networks connectivity for sUAS, a major trend across the industry. 4G and 5G enabled sUAS present new challenges, therefore corresponding parameters have to be considered, such as network loading, for instance during peak usage hours, and handover between cell towers.

Acknowledgment

This work was supported by Innovate UK funding, grant number 84765. The authors would like to thank for their helpful suggestions and insight the AiResponse consortium members, composed by Intelsius, The Drone Office, HEROTECH8, BlueBear, Cranfield University, King's College and Milton Keynes Hospital (NHS).

References

[1] "Unmanned Aerial Vehicle (UAV) Market by Point of Sale, Systems, Platform (Civil & Commercial, and Defense & Governement), Function, End Use, Application, Type, Mode of Operation, MTOW, Range, and Region - Global Forecast to 2026." https://tinyurl.com/4drt57xf

[2] M. Vierhauser *et al.*, "Interlocking safety cases for unmanned autonomous systems in urban environments," 2018. doi: 10.1145/3183440.3195035.

[3] "CAP 722: Unmanned Aircraft System Operations in UK Airspace - Guidance." https://publicapps.caa.co.uk/modalapplication.aspx?appid=11&mode=detail&id=415

[4] "CAP1861: Beyond Visual Line of Sight in Non-Segregated Airspace." https://publicapps.caa.co.uk/modalapplication.aspx?catid=1&pagetype=65&appid=11&mode=detail&id=9294

[5] M. Abramson, M. Refai, and C. Santiago, "The Generic Resolution Advisor and Conflict Evaluator (GRACE) for Unmanned Aircraft Detect-And-Avoid Systems," 2017, [Online]. Available: http://www.sti.nasa.gov

[6] M. U. de Haag, C. G. Bartone, and M. S. Braasch, "Flight-test evaluation of small form-factor LiDAR and radar sensors for sUAS detect-and-avoid applications," 2016. doi: 10.1109/DASC.2016.7778108.

[7] S. Graham *et al.*, “Multiple intruder autonomous avoidance flight test,” 2011. doi: 10.2514/6.2011-1420.

[8] J. T. Davies and M. G. Wu, “Comparative Analysis of ACAS-Xu and DAIDALUS Detect-and-Avoid Systems,” *NASA Technical Reports Server*, 2018.

[9] “SARA.” https://sara.com/tasa

[10] “SESAR Joint Undertaking.” https://www.sesarju.eu/sites/default/files/documents/reports/U-space Blueprint brochure final.PDF

[11] L. Legros, “Initial view on Principles for the U-space architecture,” 2020.

[12] M. Consiglio, C. Munoz, G. Hagen, A. Narkawicz, and S. Balachandran, “ICAROUS: Integrated configurable algorithms for reliable operations of unmanned systems,” 2016. doi: 10.1109/DASC.2016.7778033.

[13] S. Henely, “Traffic Alert and Collision Avoidance System II (TCASII),” in *Digital Avionics Handbook*, 2014. doi: 10.1201/b17545-22.

[14] M. Castle, “Traffic alert and collision avoidance system (TCAS) program office,” 2014.

[15] J. G. Lopez *et al.*, “Integration and Flight Test of Small UAS Detect and Avoid on A Miniaturized Avionics Platform,” 2019. doi: 10.1109/DASC43569.2019.9081780.

[16] ICAO, “Manual On Remotely Piloted Aircraft Systems (RPAS),” 2015.

[17] S. P. Cook, D. Brooks, R. Cole, D. Hackenberg, and V. Raska, “Defining well clear for unmanned aircraft systems,” 2015. doi: 10.2514/6.2015-0481.

[18] G. Manfredi and Y. Jestin, “Are You Clear about ‘Well Clear’?,” 2018. doi: 10.1109/ICUAS.2018.8453405.

[19] L. E. Alvarez, I. Jessen, M. P. Owen, J. Silbermann, and P. Wood, “ACAS sXu: Robust Decentralized Detect and Avoid for Small Unmanned Aircraft Systems,” 2019. doi: 10.1109/DASC43569.2019.9081631.

[20] A. Weinert, S. Campbell, A. Vela, D. Schuldt, and J. Kurucar, “Well-clear recommendation for small unmanned aircraft systems based on unmitigated collision risk,” *Journal of Air Transportation*, 2018, doi: 10.2514/1.D0091.

[21] E. Ancel, F. M. Capristan, J. v. Foster, and R. C. Condottax, “Real-time risk assessment framework for unmanned aircraft system (UAS) traffic management (UTM),” 2017. doi: 10.2514/6.2017-3273.

[22] G. Manfredi and Y. Jestin, “An introduction to ACAS Xu and the challenges ahead,” 2016. doi: 10.1109/DASC.2016.7778055.

[23] M. Kastelein and M. U. de Haag, “Preliminary analysis of ADS-B performance for use in ACAS systems,” 2014. doi: 10.1109/DASC.2014.6979522.

[24] H. Schebesta, G. Contissa, G. Sartor, A. Masutti, P. Tomasello, and D. Taurino, “Design according to liabilities: ACAS X and the treatment of ADS-B position data,” 2015.

[25] G. Corraro, F. Corraro, E. de Lellis, and L. Garbarino, “Flight tests of ADS-B traffic advisory system (ATAS) and performance comparison with other surveillance systems,” 2018. doi: 10.2514/6.2018-0286.

[26] “ADS-B – ADS-B Traffic Advisory System (ATAS).” https://www.faa.gov/nextgen/programs/adsb/pilot/atas/

[27] G. N. Szatkowski, A. Kriz, L. A. Ticatch, R. Briggs, J. Coggin, and C. M. Morris, “Airborne Radar for sUAS Sense and Avoid,” 2019. doi: 10.1109/DASC43569.2019.9081656.

[28] R. J. Stamm, J. Glaneuski, P. R. Kennett, and J. M. Belanger, “Advances in the use of NAS infrastructure and GBDAA for UAS operations,” 2018. doi: 10.1109/DASC.2018.8569723.

[29] SRC and Inc, “GBSAA RADAR SYSTEM,” 2020, [Online]. Available: www.srcinc.com

[30] E. T. Dill and M. Uijt de Haag, “3D Multi-Copter Navigation and Mapping Using GPS, Inertial, and LiDAR,” *Navigation, Journal of the Institute of Navigation*, 2016, doi: 10.1002/navi.134.

[31] R. Sabatini, A. Gardi, and M. A. Richardson, “LIDAR Obstacle Warning and Avoidance System for Unmanned Aircraft,” *International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering*, 2014.

[32] S. Ramasamy, R. Sabatini, A. Gardi, and J. Liu, “LIDAR obstacle warning and avoidance system for unmanned aerial vehicle sense-and-avoid,” *Aerospace Science and Technology*, 2016, doi: 10.1016/j.ast.2016.05.020.

[33] J. Lee, H. Lee, and D. H. Shim, “Low-swap eo sensor-based robust aircraft detection for daa technology in uas integration,” 2019. doi: 10.2514/6.2019-3049.

[34] K. J. Monk, J. Keeler, R. Conrad Rorie, G. Sadler, and C. Smith, “UAS pilot performance comparisons with different low size, weight and power sensor ranges,” 2020. doi: 10.1109/DASC50938.2020.9256615.

[35] W. K. Ang, W. S. Teo, and O. Yakimenko, “Enabling an EO-Sensor-Based Capability to Detect and Track Multiple Moving Threats Onboard sUAS Operating in Cluttered Environments,” 2019. doi: 10.1145/3387304.3387305.

[36] R. Usamentiaga and D. F. García, “Infrared Thermography Sensor for Temperature and Speed Measurement of Moving Material,” *Sensors (Basel, Switzerland)*, 2017, doi: 10.3390/s17051157.

[37] B. Harvey and S. O’young, “Acoustic detection of a fixed-wing UAV,” *Drones*, 2018, doi: 10.3390/drones2010004.

[38] X. GUAN, R. LYU, H. SHI, and J. CHEN, “A survey of safety separation management and collision avoidance approaches of civil UAS operating in integration national airspace system,” *Chinese Journal of Aeronautics*. 2020. doi: 10.1016/j.cja.2020.05.009.

[39] “AGI: STK 12.1.” https://www.agi.com/new-stk/stk-12-1

[40] “Importing Actual 3D Models From Google Maps.” https://blog.exppad.com/article/importing-actual-3d-models-from-google-maps

[41] “blender.org - Home of the Blender project - Free and Open 3D Creation Software.” https://www.blender.org/

[42] “Cesium ion – Cesium.” https://cesium.com/platform/cesium-ion/

[43] “MATLAB - MathWorks - MATLAB & Simulink.” https://uk.mathworks.com/products/matlab.html

2021-11-15

Detect and avoid considerations for safe sUAS operations in urban environments

Celdran Martinez, Victor

IEEE

https://doi.org/10.1109/DASC52595.2021.9594407